

*\*\*TITLE\*\**

*ASP Conference Series, Vol. \*\*VOLUME\*\*, \*\*PUBLICATION YEAR\*\**

*\*\*EDITORS\*\**

## The Heating of the Intra Cluster Medium

Paolo Tozzi

*Oss. Astronomico di Trieste, via G.B. Tiepolo 11, 34100 Trieste – Italy*

**Abstract.** X-ray observations indicate that non-gravitational processes play a key role in determining the distribution of the diffuse, X-ray emitting gas in clusters of galaxies (ICM). The effect of non-gravitational processes is imprinted in the ICM as an entropy minimum. Preheating models assume that the entropy minimum is present in the cosmic baryons well before collapse. On the other hand, observations of baryons in Ly $\alpha$  clouds show only a modest extra heating, ruling out the presence of such an entropy plateau in the majority of low-density baryons at high  $z$ . The problem is avoided in the *internal heating* scenario, where the heating occurs only inside virialized structures. However, for internal heating the energy needed to build the entropy minimum is in excess of 1 keV per particle. It is not clear which kind of source can heat the baryons: SNe seem to be inefficient by a factor of 3 or more. This energy crisis must be solved by other sources (like AGNs), unless we are missing some key aspect of the heating mechanism. The main questions for the next years will be: when and where is the excess entropy produced, and by which mechanism?

### 1. Introduction

Observations in the X-ray band provided many evidences for non-gravitational heating of the diffuse, high density baryons in the potential wells of groups and clusters of galaxies (Intra Cluster Medium, or ICM). The first evidence is the shape of the L-T relation, which is steeper than the self-similar behaviour  $L \propto T^2$  predicted in the case of gravitational processes only. Recently, Ponman, Cannon & Navarro (1999, PCN; see also panel B in Figure 1) found directly an entropy excess with respect to the level expected from gravitational heating in the center of groups. The entropy is defined as  $S \equiv \log K$ , where  $K = kT/\mu m_p \rho_e^{2/3}$ ,  $kT$  is the temperature,  $\rho_e$  is the mass density of the ionized plasma, and  $\mu$  is the mean molecular weight (see also Balogh, Babul & Patton 1999). The excess entropy induces a larger pressure support that decreases the density in the central regions. This, in turn, rapidly decreases the X-ray luminosity which is proportional to the square of the density. The effect is stronger in small groups, where the energy responsible for the entropy is comparable to the gravitational one, while clusters, where gravity is dominant, are mostly unaffected. This produces a steepening of the L-T relation. Non-gravitational heating of the ICM is expected also on the basis of observations of an average metallicity  $Z \simeq 0.3 Z_\odot$ . In fact, SNe are likely to be responsible of heating

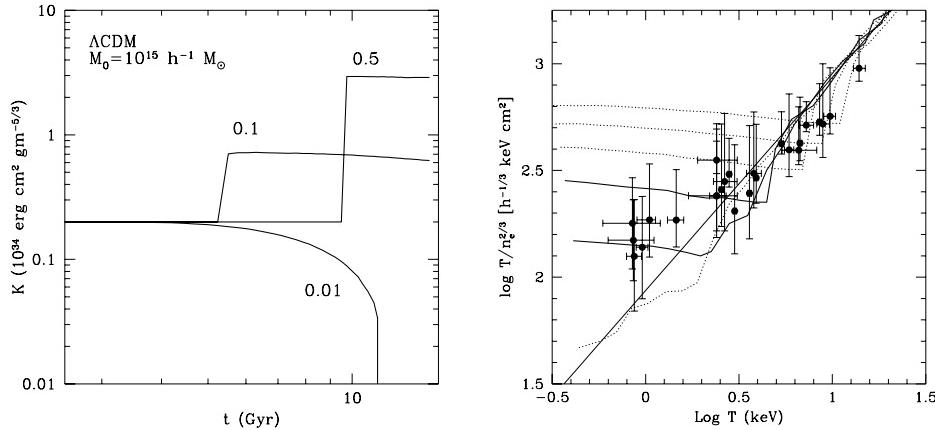


Figure 1. Left: The evolution of the adiabat  $K$  for three baryonic shells (including 1%, 20% and 50% of the total baryons at  $z = 0$ ) as a function of cosmic epoch  $t$  ( $\Lambda$ CDM cosmology, for a final mass of  $10^{15} h^{-1} M_\odot$ ,  $K_* = 0.3 \times 10^{34} \text{ erg cm}^2 \text{ g}^{-5/3}$ ). The sharp discontinuity occurs at the shock (TN). Right: the relation between the entropy at  $r = 0.1R_v$  and the emission-weighted temperature for  $\Lambda$ CDM at redshift  $z = 0$  for different values of the excess entropy  $K_* = 0.6 - 0.5 - 0.4 - 0.3 - 0.2 - 0.1 \times 10^{34} \text{ erg cm}^2 \text{ g}^{-5/3}$ , from top to bottom (TN). The straight line is the self similar case from N-body simulations (see PCN).

and polluting the ICM at the same time. For example, Finoguenov, Arnaud & David (2000) derived about 1 keV per particle from SNe Ia from the abundance of Silicon. It should be understood how much of this energy goes into the ICM and if it is enough to build the observed entropy plateau.

## 2. The entropy distribution of the ICM

A first step to understand the role of entropy is to investigate its effect on the X-ray properties of groups and clusters of galaxies. The simplest choice is that of the *external heating* models (or preheating, see Tozzi & Norman 2001, hereafter TN). If the excess entropy is present in the baryons before collapse, it will be preserved in the cores of dark matter halos after virialization. In virtue of the extra pressure support, in fact, the gas is accreted adiabatically without shock heating. The entropy has also the effect of suppressing the radiative cooling in the central regions (due to the low density). The evolution of the adiabat  $K$  for the accreted shells is shown in Figure 1 (left). The pre-collapse entropy  $K_*$  is preserved in the core of groups, in agreement with observations (Figure 1, right).

This model allows to trace the evolution of X-ray luminosity and temperature of groups and clusters after assuming a Press & Schechter-like law for the accretion rate of baryons (see TN). In Figure 2 we show that the evolution corresponds to tracks moving along the local  $L-T$  relation. Thus, a constant  $L-T$

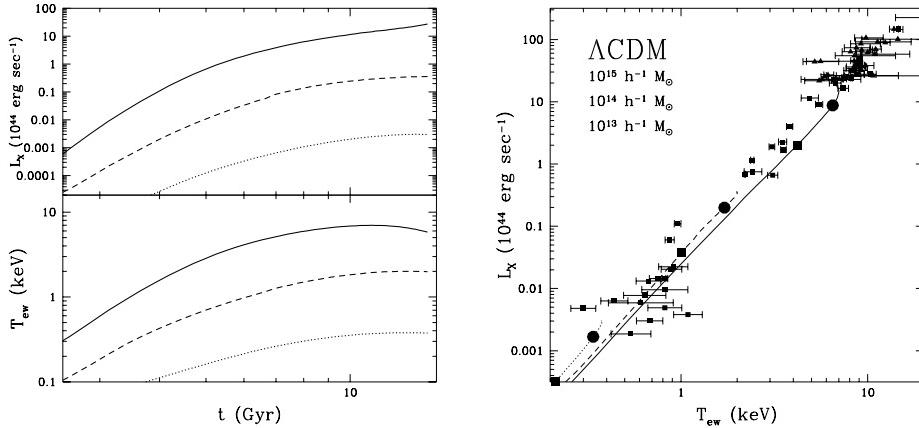


Figure 2. Left: The evolution of the bolometric luminosity  $L_X$  and of the emission-weighted temperature  $T_{ew}$  is shown as a function of cosmic epoch for a final mass of  $10^{15} - 10^{14} - 10^{13} h^{-1} M_\odot$  (solid, dashed and dotted lines respectively) for a  $\Lambda$ CDM cosmology, with a constant initial adiabat  $K_* = 0.3 \times 10^{34} \text{ erg cm}^2 \text{ g}^{-5/3}$ . Right: The evolutionary tracks along the local  $L$ - $T$  relation for the halos on the left. The large squares and circles mark redshifts 1 and 0.5 respectively. Data from Allen & Fabian (1998), Arnaud & Evrard (1999), Ponman et al. (1996).

is predicted up to  $z \simeq 1$ , in agreement with observations (Mushotzky & Scharf 1997, Borgani et al. 2001). The entropy level that satisfies the observations is between  $K_* = 0.2 - 0.3 \times 10^{34} \text{ erg cm}^2 \text{ g}^{-5/3}$  (see Figure 1 and 2).

In Figure 3 we show surface brightness and temperature profile for a rich cluster and a group in the external entropy scenario (from Tozzi, Scharf & Norman 2001, hereafter TSN). The treatment in TSN allows to trace the density profile at radii larger than the virial one, in order to check whether it is possible to detect the infalling gas. The first case is the most favourable from the point of view of the observations, since the very high external temperature make the infalling gas detectable in emission around rich clusters. This case is expected if the external gas reached a very high entropy at redshift zero or if it reached large overdensities due to infalling substructures (see TSN). Inside the shock radius but outside the adiabatic core, the entropy profile is well approximated by  $K \propto R^{1.1}$  (see Figure 4, solid lines), a behaviour which is also found in N-body simulations (see S. Borgani, these Proceedings).

The second case is for a group with a constant external entropy  $K_* = 0.3 \times 10^{34} \text{ erg cm}^2 \text{ g}^{-5/3}$ . At this mass scale, the external entropy inhibits shock heating and the accretion is entirely adiabatic. The entropy profile is flat and there is no discontinuity clearly separating the accreted gas from the infalling, external gas. In this case a substantial temperature gradient is expected in the outer regions. So far, the temperature profile for groups has been observed only in the very central regions, where no significant gradients are predicted.

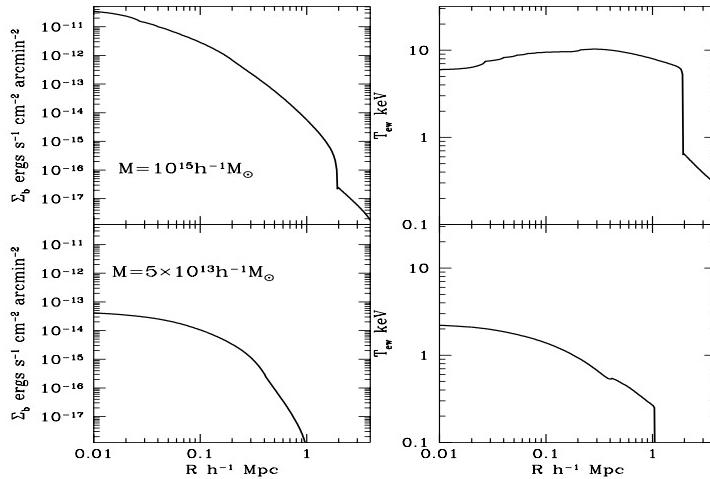


Figure 3. Surface brightness and projected temperature profiles for a cluster of  $M = 1.4 \times 10^{15} h^{-1} M_{\odot}$ , tCDM,  $K_* = 3 \times 10^{34}(1+z)^{-2}$   $\text{erg cm}^2 \text{ g}^{-5/3}$  (top panels) and  $M = 5 \times 10^{13} h^{-1} M_{\odot}$ ,  $\Lambda$ CDM,  $K_* = 0.3 \times 10^{34} \text{ erg cm}^2 \text{ g}^{-5/3}$  (lower panels), from TSN.

### 3. The energy crisis

The external heating scenario is appealing, but it has a problem: the excess entropy cannot be spread uniformly into the cosmic baryons at high redshifts since this would make the Ly $\alpha$  forest to disappear. Recently, it has been estimated that the level of preheating in the Ly $\alpha$  clouds is of the order of few  $10^4 K$  (Cen & Brian 2001), corresponding to an entropy level more than one order of magnitude lower than that observed in groups. A possible solution is that only the baryons that end up in the cores of groups and clusters are heated by a biased distribution of sources. Such a warm, low density gas would be unobservable at high  $z$ , and can be detected as OVI absorption systems at low (Tripp, Savage & Jenkins 2001) or at intermediate  $z$  (Reimers et al. 2001).

Another solution is that the ICM is heated after the collapse. Of course, for a given entropy level, the much higher density implies a much higher energy input. An energy budget of 1–2 keV per particle seems to be required to reproduce the entropy floor (see also Wu, Fabian & Nulsen 2000, Valageas & Silk 1999) and entropy profiles very similar to the ones predicted in the external heating scenario (see Figure 4, dashed lines). We recall that the preheating scenario requires few tenths of keV (with a strict lower limit of 0.1 keV, TN) since the gas is heated at about the background density. Therefore, the internal scenario requires an energy input 3–10 times higher than that in the external scenario.

Despite the SNe can provide a large amount of energy, their efficiency in heating the gas is unknown. In particular, if the heated gas has high density, the thermal energy received from SNe is easily radiated away, with a small net increase in the gas entropy. Simulations with a self-consistent SNe heating

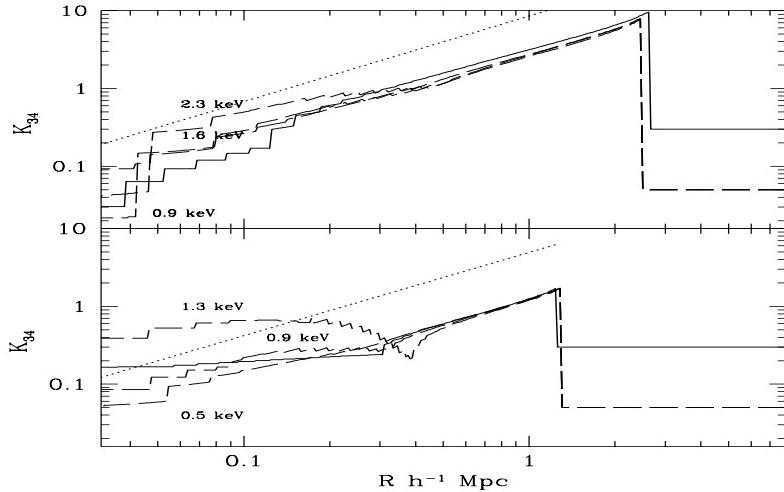


Figure 4. The entropy profiles in the external (continuous lines) and the internal (dashed lines) scenario for a rich cluster ( $M = 10^{15}h^{-1}M_{\odot}$ , upper panel) and a small cluster ( $M = 10^{14}h^{-1}M_{\odot}$ , lower panel). The entropy level is  $K_{34} = 0.3$  (in units of  $10^{34} \text{ erg cm}^2 \text{ g}^{-5/3}$ ) in the external scenario. In the internal scenario, a total energy of 1–2 keV per particle is released, as shown by the labels. The dotted line is the power law  $K \propto R^{1.1}$  (see TSN).

model plugged in, tell us that they can hardly increase the entropy to the observed level in groups and clusters (see talks by S. Borgani). However we still do not have a complete scenario to follow the heating and enrichment by SNe and the consequent entropy history of the surrounding baryons.

A recent progress in this direction has been made by Pipino et al. (these Proceedings). They computed metals and energy dumped in the ICM starting from the observed luminosity function of cluster galaxies. The efficiency of TypeII and TypeIa SNe is computed assuming a spherical gas distribution around galaxies. The energy per particle dumped in the ICM as a function of redshift is plotted in Figure 5 (black stripe). We also plotted the energy required to obtain the entropy  $K_* = 0.2 - 0.3 \times 10^{34} \text{ erg cm}^2 \text{ g}^{-5/3}$  at a given redshift in virialized structures (upper stripe) and in the background baryons (lower stripe). It turns out that SNe can contribute a substantial amount of the required energy. To understand in detail their role in the entropy history of the ICM, we must run detailed hydrodynamical simulations (see talks by R. Bower and A. Ferrara) to follow the heating along with the accretion of the diffuse baryons and the cooling of the low entropy gas. If SNe will be shown to be inadequate for this job, it will be necessary to look for other sources, like AGNs, which in principle can provide the largest amount of energies (but see Yamada & Fujita 2001). Both X-ray observations and theoretical modelling will be crucial in the next few years.

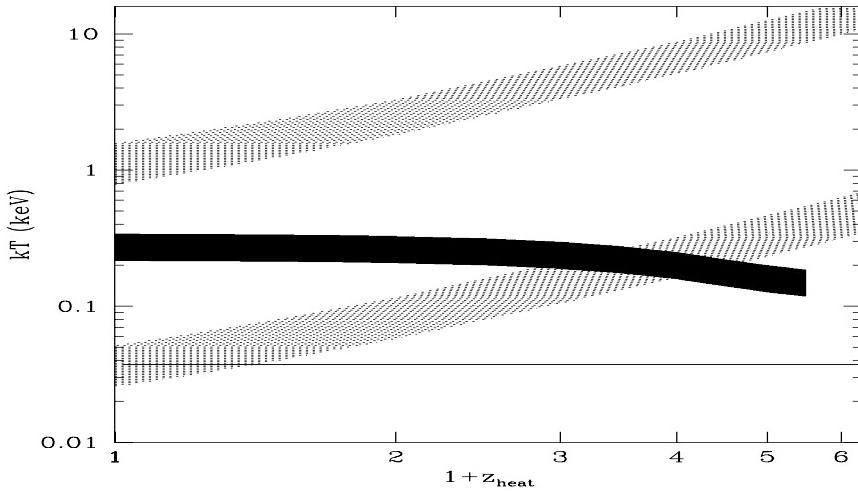


Figure 5. The upper and lower stripes show the required energy per particle needed to obtain an excess entropy of  $K_* = 0.2 - 0.3 \times 10^{34}$  erg cm $^2$  g $^{-5/3}$  in virialized structures and in the diffuse baryons at the background density respectively. The solid stripe is the energy per particle dumped in the ICM by Type II and TypeIa SNe after the calculation of Pipino et al. (2001). The solid line is the upper limit for the extra energy present in Ly $\alpha$  clouds (Cen & Bryan 2001).

## References

- Allen, S.W., & Fabian, A.C. 1998, MNRAS, 297, 63L  
 Arnaud, M., & Evrard, A.E. 1999, MNRAS, 305, 631  
 Balogh, M.L., Babul, A., & Patton, D.R. 1999, MNRAS, 307, 463  
 Cen, & Bryan 2001, ApJ, 546, 81L  
 Finoguenov, A., Arnaud, M. & David, L.P. 2001, ApJ in press, astro-ph/0009007  
 Mushotzky, R. F., & Scharf, C. A. 1997, ApJ, 482, 13  
 Ponman, T. J., et al. 1996, MNRAS, 283, 690  
 Ponman, T. J., Cannon, D. B., & Navarro, F.J. 1999, Nature, 397, 135 (PCN)  
 Reimers, D., et al. 2001, A&A submitted, astro-ph/0106097  
 Tozzi, P., & Norman, C. 2001, ApJ, 546, 63 (TN)  
 Tozzi, P., Scharf, C., & Norman, C. 2000, ApJ, 542, 106 (TSN)  
 Tripp, T.M., Savage, B.D., & Jenkins, E.B. 2001, ApJL in press, astro-ph/0003277  
 Valageas, P., & Silk, J. 1999, A& A, 350, 725  
 Yamada, M., & Fujita, Y. 2001, astro-ph/0105102  
 Wu, K. K. S., Fabian, A. C., & Nulsen, P. E. J. 1999, MNRAS, 318, 889